Toward Better Intraseasonal and Seasonal Prediction: Verification and Evaluation of the NOGAPS Model Forecasts

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LONG TERM GOALS

The long-term goals of this project are to understand the key physical processes for realistic simulation and skillful prediction of the MJO and to improve the intraseasonal to seasonal prediction skills of the Navy's global numerical weather forecast models.

OBJECTIVES

Intraseasonal and seasonal prediction provides important information for decision-making and resource management, and has received increased attention in recent years. Despite substantial progresses in numerical modeling in the past few decades, skillful seasonal prediction remains a challenge for many models. Verification and evaluation of model forecasts can offer users necessary information on the model prediction skills and uncertainties, and provide model development teams with useful information on model improvements.

The project has two specific objectives:

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i) Evaluate the intraseasonal and seasonal predictions of the Navy's global models (previously NOGAPS and now NAVGEM) against reanalysis data and satellite observations, and assess the prediction skills of the models;

ii) Evaluate the model parameterizations in different climate regimes, identify error sources, and provide the model development teams with concrete information on model deficiency and recommendations on model improvement.

APPROACH

With the rapid advancement of computing technologies, the spatial resolutions of global models have become higher and higher, but many important physical processes, such as cumulus convection, cloud microphysics as well as turbulent mixing in the planetary boundary layer, still can not be resolved explicitly by numerical models. These subgrid processes have to be parameterized based on the grid-scale variables. Physical parameterization has been and will remain a major source of errors and uncertainties for both numerical weather forecasts and climate predictions.

The overarching objective of the ONR DRI, "Unified parameterization for seasonal prediction", of which this project is part of, is to develop unified model parameterization for different spatio-temporal scales that are suitable for both short-term and extended range forecasts. Systematic evaluations of the model forecasts are an indispensable part of this team effort. Physics-orientated evaluations can help to identify the model deficiency and provide useful guidance on the development of new schemes, while the examination of different circulation systems, such as convective coupled waves, monsoon, and the MJO, helps to understand how the simulated physical processes interact at different spatio-temporal scales and impact the short-term and extended range forecasts.

The NOGAPS and NAVGEM forecasts and simulations will be evaluated in a systematic way with a focus on the following aspects: i) the mean states and major climate components (including monsoons, the ITCZ, the Hadley Circulation, and etc.); ii) the low-frequency modes, including the MJO, ENSO, NAO and the related teleconnection patterns; iii) cloud properties/structures and moist convective processes in different climate regimes.

On the intraseasonal to seasonal time scales, the low-frequency modes, such as the MJO and ENSO, provide an additional source of predictability other than the lower boundary conditions (SST and land surface conditions). The representation of such modes in a model thus needs to be evaluated. The mean states of model forecasts are important because a realistic basic state is a prerequisite for the realistic simulation of such low-frequency modes (Kim et al. 2011). Clouds and their associated feedback processes are one of the greatest uncertainties in numerical models. Using satellite observations (including TRMM, AIRS, CloudSat/CALIPSO), we examined the cloud properties and structures in the NAVGEM in different climate regimes. To facilitate the comparison between model simulations and satellite observations, we employed the observation simulator package (COSP) developed by the Cloud Feedback Model Intercomparison

Project (CFMIP). COSP converts the model hydrometers (condensate and precipitation) into pseudo-satellite observations. The synthesized cloud properties derived from model forecasts will be evaluated against the CloudSat/CALIPSO. This approach avoids the uncertainties from inversion models used in satellite retrieval algorithms and allows models to be evaluated against satellite retrievals in a consistent way.

WORK COMPLETED

We continued to develop diagnostic tools for model evaluation using both performance-oriented metrics and physics-oriented metrics. In particular, we

i) used version-7 Special Sensor Microwave Imager Sounder (SSMIS) polar orbiting satellite data to evaluate the precipitation-column water vapor (CWV) relationship in the operational forecasts;

ii) examined the impacts of different precipitation components (deep convective vs. stratiform) and the associated heating profiles on the large scale circulations through the diagnosis of apparent heat source (Q1) and moisture sink (Q2);

iii) examined the forecast errors of an unusual cutoff cyclone in the NAVGEM and GFS operational forecasts and investigated the possible causes;

iv) developed an original approach to examine the variability of the regional Hadley Circulation over different basins and to investigate its impacts on tropical cyclone (TC) activity; examined the large-scale circulations in the NAVGEM model and the source of predictability for the seasonal variation of the Atlantic TCs.

We have been working closely with Drs. James A. Ridout and Ming Liu at the NRL to examine the underlying causes for the model deficiency, and working with Mr. Tim Whitcomb to incorporate some diagnostic codes into the evaluation package of the NAVGEM system.

RESULTS

a) Development of diagnostic tools to evaluate the model precipitation processes against satellite retrievals and reanalysis data

SSMIS has simultaneous retrieval of the precipitation rate and the CWV, and provides an ideal standard to examine the relationship between precipitation and moisture. The distribution of the CWV over each basin is shown in Fig. 1. The SSMIS retrieval reveals the different column moisture distributions over different basins. The western Pacific region is characterized by a prominent peak between 55 - 60 mm. The eastern Pacific has a bi-modal distribution with the primary peaking frequency of occurrence around 30 mm and a secondary one around 57 mm, which reflects the dry condition over the eastern South Pacific (with prevailing marine stratus) and the moist condition in the ITCZ region.

Compared to SSMIS, a dry bias is found in the NOGAPS forecasts. The CWV of the peaking frequency of occurrence in the NOGAPS forecasts is more than 5 mm lower than

that in the SSMIS over the Indian Ocean and the western Pacific. Over the eastern Pacific and the Atlantic, the NOGAPS forecasts do not capture the bi-modal distribution of the CWV, and the CWV of the primary peaking frequency is up to 10 mm lower than that in the SSMIS.

A weaker dry bias is also present in the distribution of the CWV from the NOGAPS analysis. A close look shows a small but discernible increase in the dry bias over all the basins from 1-day to 5-day forecasts, indicating deficiencies in the model physics.

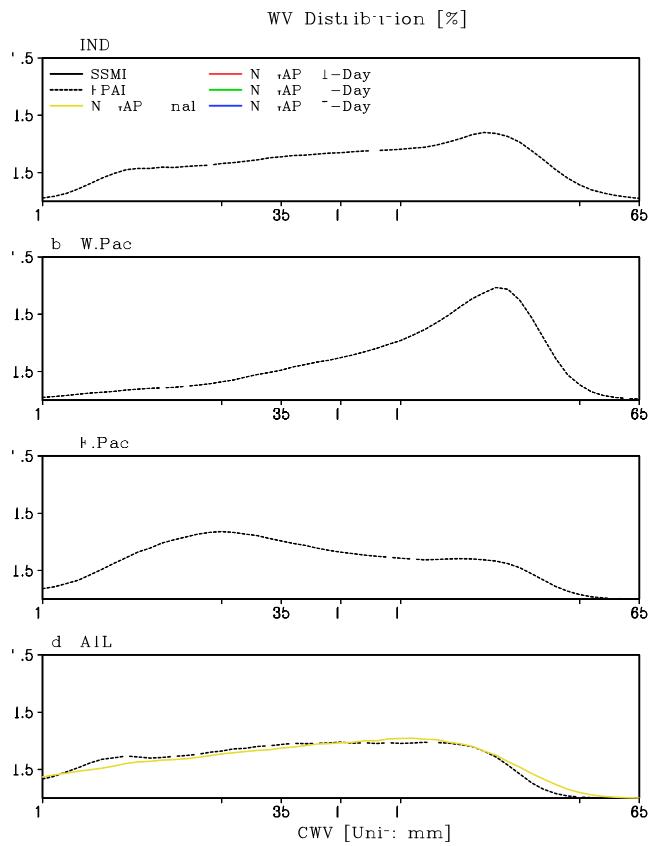

Fig. 1 The distribution (unit: %) of CWV over different ocean basins. The black solid (dotted) lines represent the SSMIS (ERAI) CWV; yellow lines represent the NOGAPS analysis; and the red/green/blue lines represent 1/3/5-day NOGAPS forecasts, respectively.

Figure 2 shows the vertical cross sections of the zonally averaged Q1 derived from the ERAI, the NOGAPS 3-day and 5-day forecasts over different basins. The impacts on large-scale atmospheric circulations associated with the thermodynamic biases are examined in Fig. 3. Over the western Pacific (south of 10ºS), the NOGAPS forecasts capture the lower-tropospheric heating and cooling above, which is associated with the marine stratocumulus. But over the western Pacific monsoon regions (10ºS - 20ºN), the diabatic heating rate is significantly underpredicted and has a more top-heavy profile than that derived from the ERAI. The biases in precipitation and heating induce biases in the regional Hadley Circulation (Fig. 3). Compared to the ERAI, tropical easterlies (trade winds) and subtropical westerlies in the northern hemisphere are both weaker in the NOGAPS forecasts, while the tropical easterlies south of 10ºS are overestimated. The

analysis suggests a weaker Hadley Circulation over the western Pacific, implying reduction in the poleward heat and momentum transports from the tropics.

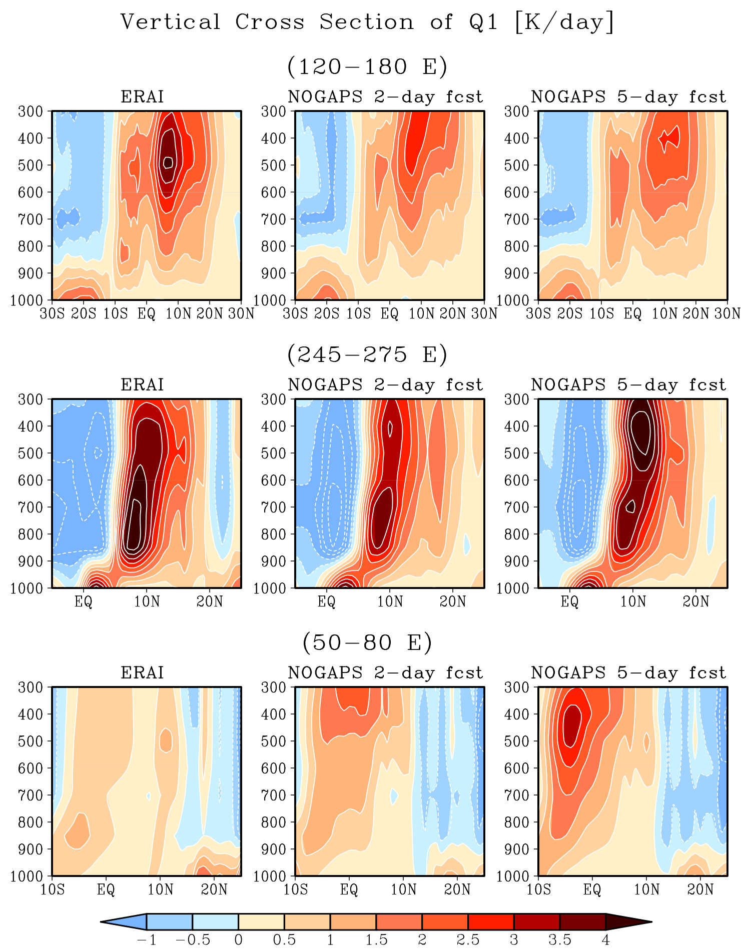

Fig. 2 The vertical cross sections of the zonally averaged diabatic heating rate (Q1) during boreal summer 2008-2011 for the ERAI, NOGAPS 2-day and 5-day forecasts over the western Pacific (120ºE-150ºE) (top), eastern Pacific (245ºE-275ºE) (middle) and Indian Ocean (50ºE-80ºE) (bottom). Unit: K day^{-1}.

In the eastern Pacific ITCZ region, the lower-tropospheric heating shifts northward and upward with the forecast lead times. The heating profile in the NOGAPS 5-day forecast is more top-heavy compared to that in the ERAI. The westerlies to the south of the ITCZ shift northward with the heating. Recall that vertical shear is an important environmental factor affecting TC formation and intensification. The biases in the large-scale flow may induce errors in TC frequency, track and intensity in the NOGAPS forecasts.

Figure 2 also shows that both the diabatic cooling north of 10ºN and heating south of 10ºN are significantly overpredicted. Similar to the western Pacific and the eastern Pacific, the heating over the South Indian Ocean is also more top-heavy than that in the ERAI. This is probably due to the model deficiencies in representing shallow convection

or stratiform precipitation process, or both. The bottom rows in Fig. 3 reveal a weaker cross-equatorial flow (including Somali Jet) over the Indian Ocean in the NOGAPS 5-day forecast (southerlies weakened by more than 30%). Weaker cross-equatorial flow implies reduced moisture transport, which may affect the MJO initiation and the monsoon onset over the North Indian Ocean. All the biases in the large-scale atmospheric circulations amplify with the NOGAPS forecast lead times (right column) and are closely related to the biases in the diabatic heating and precipitation fields.

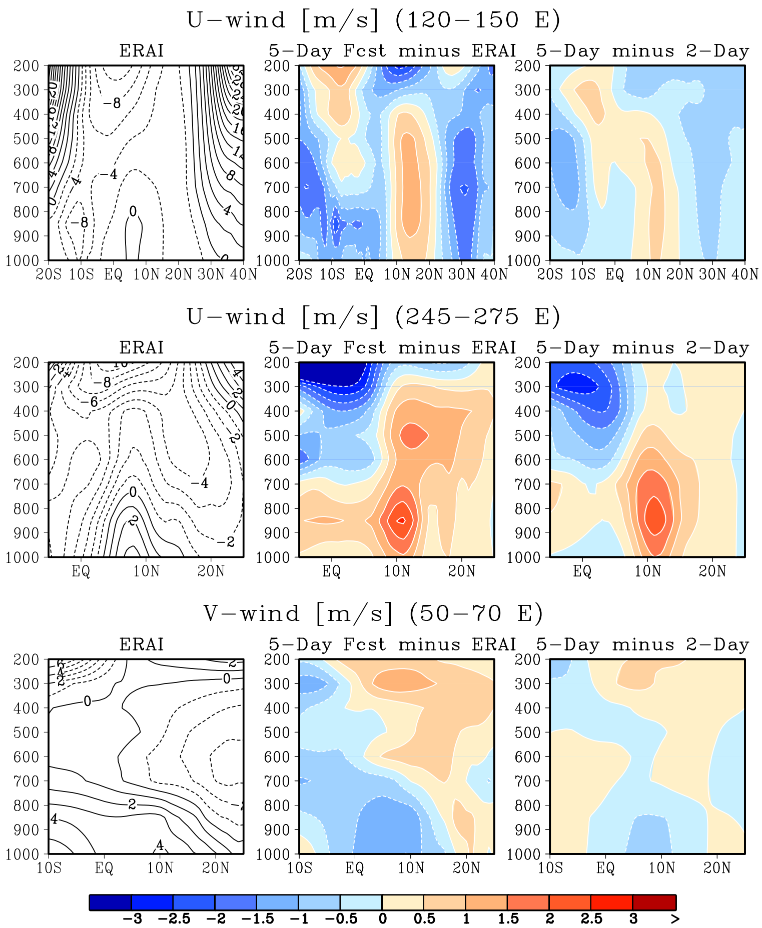

Fig. 3 The vertical cross sections of the zonally averaged zonal (U-wind) and meridional (V-wind) winds during boreal summer 2008-2011 for the ERAI (left), NOGAPS 5-day forecasts minus the ERAI (middle), and NOGAPS 5-day minus the NOGAPS 2-day forecasts (right) over the western Pacific (120ºE-150ºE) (first row), eastern Pacific (245ºE-275ºE) (second row), and Indian Ocean (50ºE-80ºE) (third row).

b) *Evaluation of the NAVGEM operational forecasts*

The cutoff low in early May 2013 over Tennessee was a remarkable and unusual phenomenon, with the cutoff extending up to 100 hPa. This cutoff low turned out to be a challenge for NWP models. As shown in Fig. 4, the forecast skill of the GFS and NAVGEM both dropped substantially beyond 3-day forecasts. The former significantly

underpredicted the intensity of the cutoff cyclone, while the latter displaced the cutoff cyclone more than 10 degrees northward.

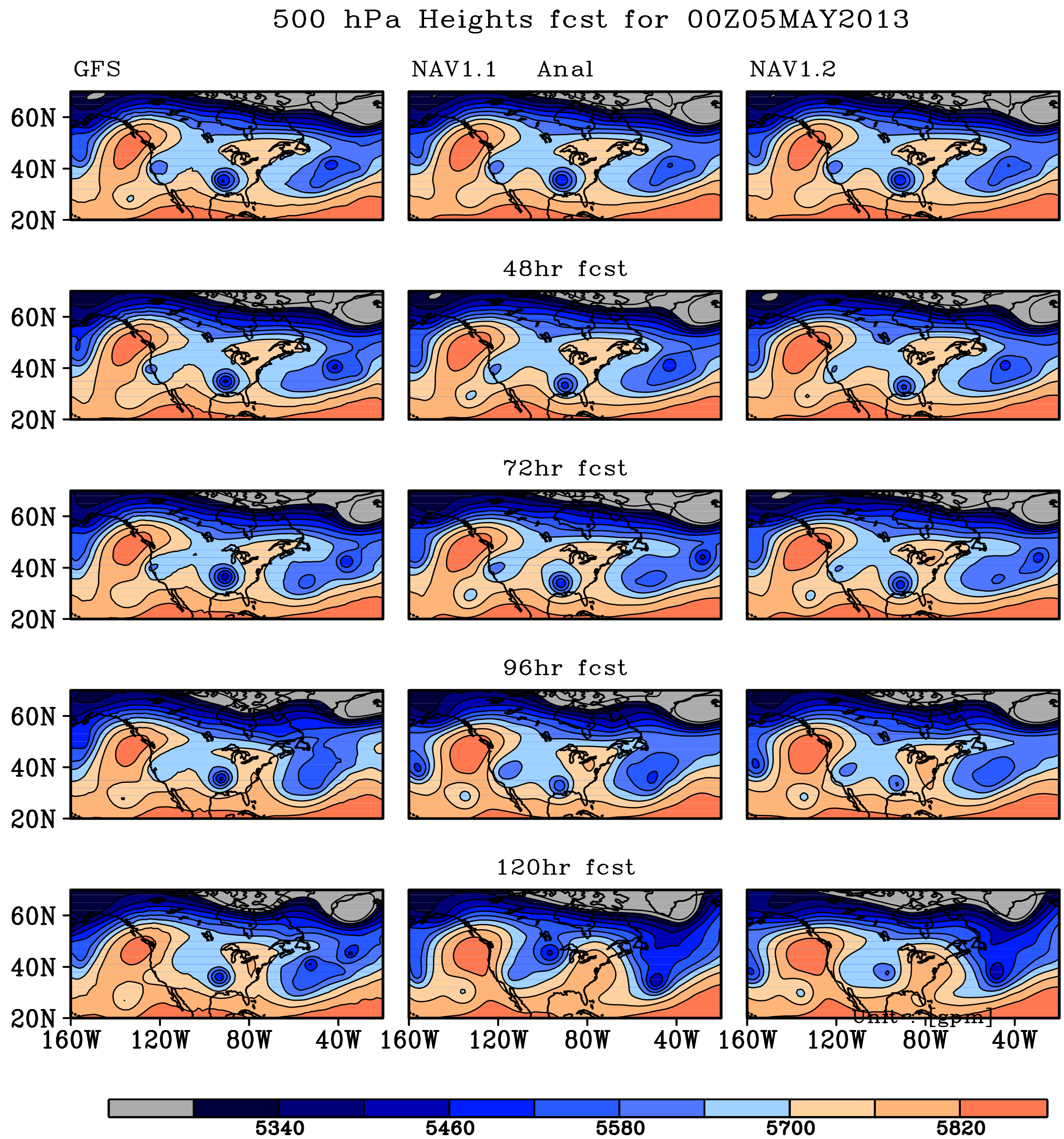

Fig. 4 500 hPa geopotential heights from the analyses and forecasts of the GFS, the operational NAVGEM model (NAV1.1) and a development version of the NAVGEM model (NAV1.2) verified at 00Z 05 May 2013.

It was found that the errors of the 96-hour and 120-hour forecasts in the GFS and the NAVGEM have a similar wave-train pattern spanning from the North Pacific to the North Atlantic (Fig. 5). This similar error pattern suggests that the large errors may be related to the flow instability. It was also found that the model errors are associated with cold biases over the land and warm biases over the ocean (not shown). The adoption of

EDMF and Xu-Randall cloud fraction scheme in NAVGEM 1.2 (right panels in Fig. 4) reduces the temperature biases and improves the location and intensity of the cut-off low.

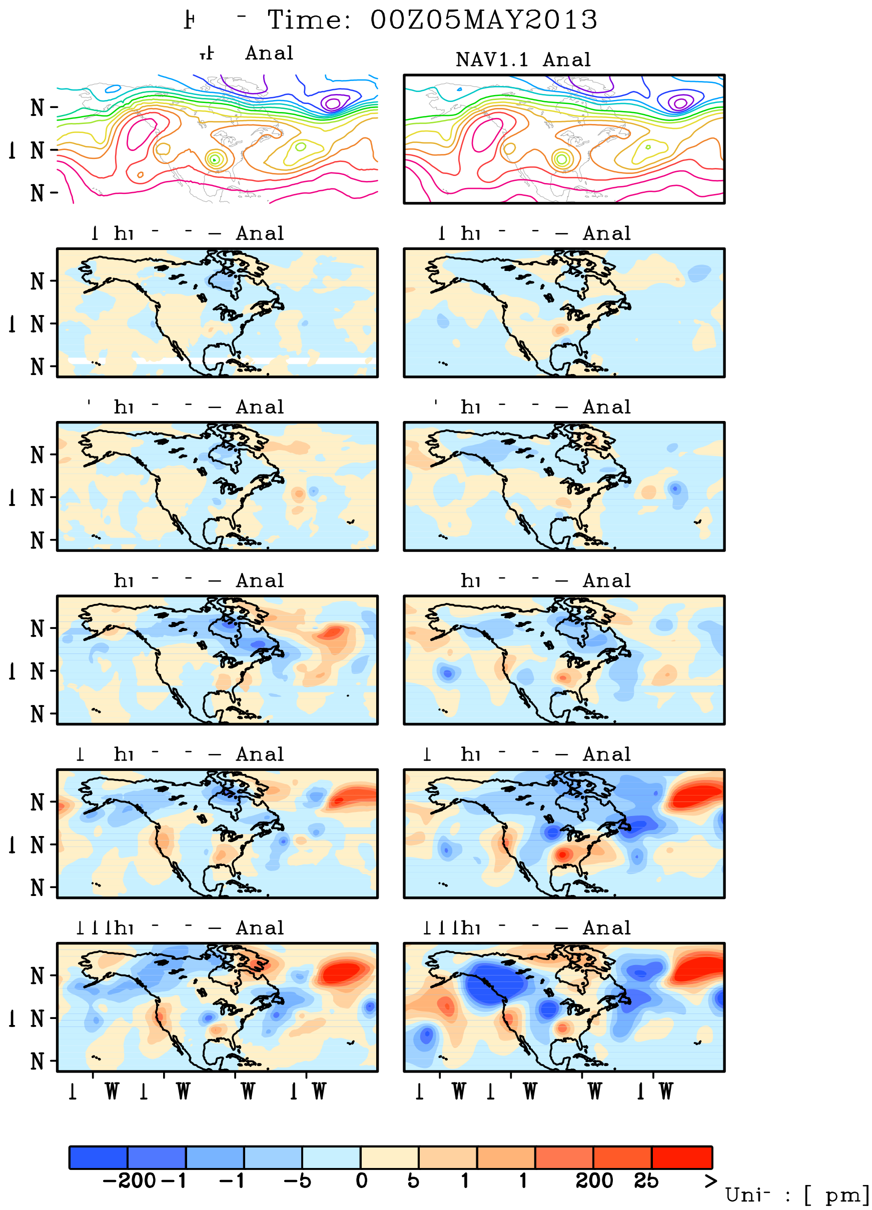

Fig. 5 500 hPa geopotential heights from the GFS and NAVGEM analyses (top panels) and the forecast errors (defined as the differences from the analysis field) with different forecast lead times.

c) Evaluation of the interannual variability of regional Hadley Circulation and predictability of TC activity

The Hadley Circulation is one of the primary components of the large-scale circulation in the atmosphere. It consists of two thermally direct overturning cells, in which air rises near the equator, diverts poleward near the tropopause, sinks in the subtropics, and

returns equatorward near the surface. Due to the Coriolis force, the upper-level poleward flow turns eastward and contributes to the subtropical westerly jet. Similarly, the equatorward flow turns westward and results in the prevailing trade winds in the lower troposphere. Associated with the ascending branch of Hadley Cells, the ITCZ is featured by a band of heavy precipitation, cyclonic relative vorticity and relatively low surface pressure. The variability of the Hadley Circulation is thus closely related to different aspects of the tropical climate, such as the precipitation distribution, low-level convergence and relative vorticity, as well as the tropospheric humidity and vertical wind shear.

A new method was developed to define the regional Hadley Circulation (HC) in terms of the meridional streamfunction. The interannual variability of the Atlantic HC in boreal summer was examined using the EOF analysis. The leading mode (M1) explains more than 45% of the variances, and is associated with the intensity change of the ITCZ (Fig. 6).

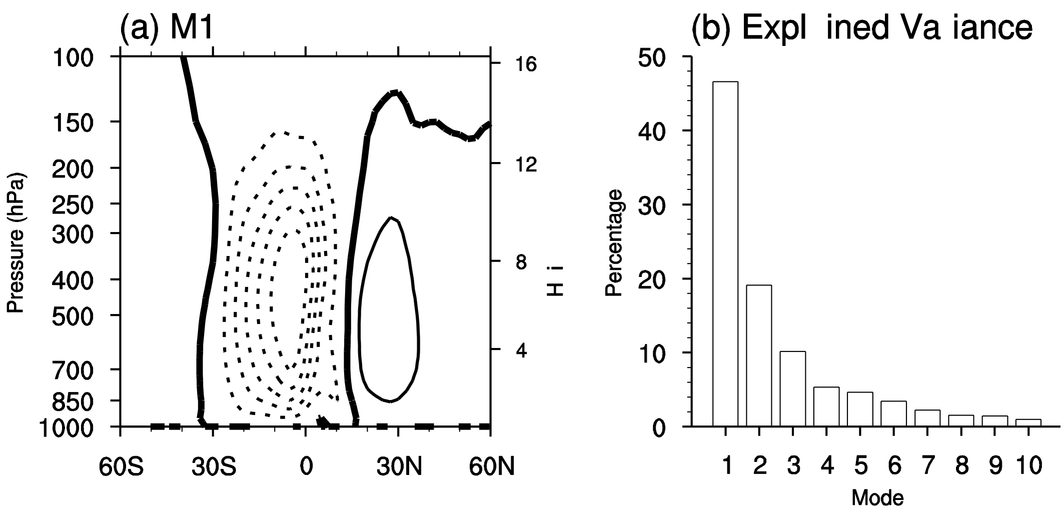

Fig. 6 The EOF analysis of Meridional Circulation (JAS). (a) The leading mode (M1); (b) variance explained by the first 10 modes.

M1 is has strong impacts on the TC activity over the Atlantic Main Development Region (MDR). In the positive phase of M1 (when the ITCZ is stronger than normal), there are more TCs forming over the MDR with a larger fraction intensifying into major hurricanes. In the negative phase of M1, the Atlantic TC genesis frequency is lower than normal, and the genesis locations shift northwestward to the Gulf of Mexico and the western North Atlantic (Fig. 7).

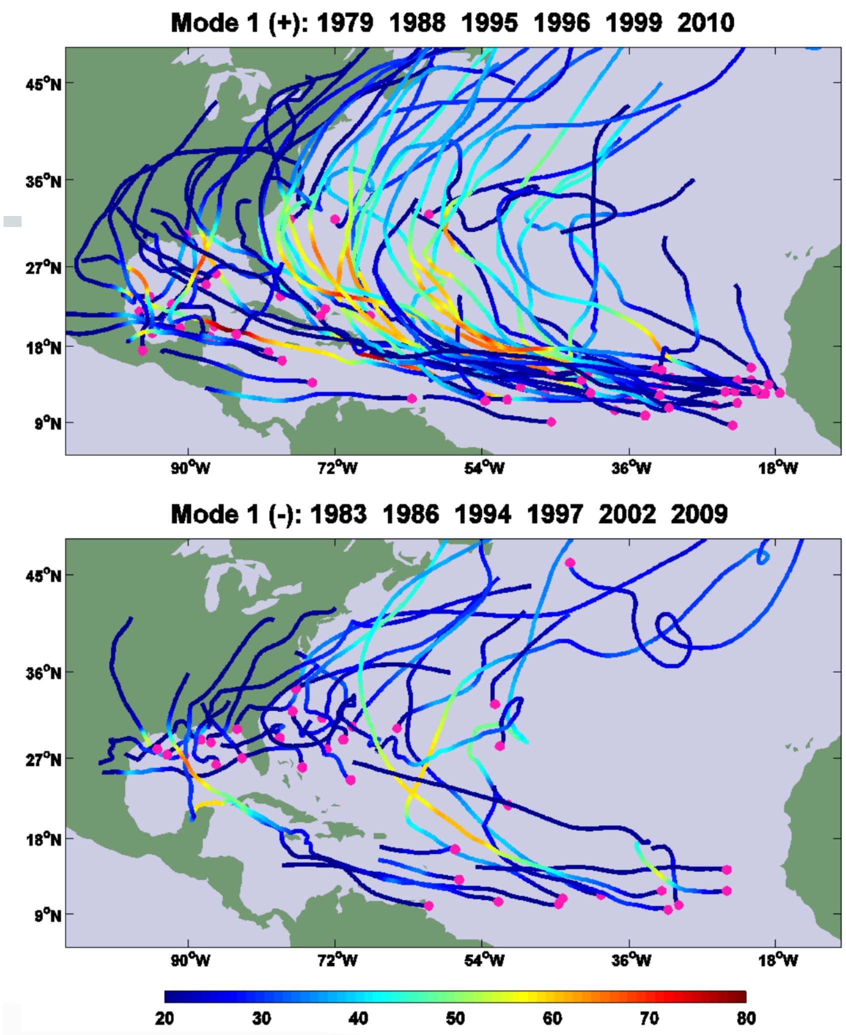

Fig. 7 Storm track, intensity and genesis location (JAS) for the positive and negative phases of M1. Genesis locations are indicated by the pink dots, and the storm intensity in terms of the maximum surface wind speed (m s^{-1}) is indicated by colors of storm tracks. The composite years for each phase are listed at the top of each plot.

It is found that M1 is significantly correlated to multiple climate factors (Fig. 8), including ENSO, AMM, NAO, relative SST and the Sahel rainfall. Our analyses show that M1 is a mode unifying both dynamic and thermodynamic factors to impact Atlantic TC activity. The positive phase of M1 is characterized by weaker vertical wind shear, higher water vapor content throughout the troposphere, stronger low-level convergence,

as well as more propitious TEW activity, all of which are favorable for the TC formation and intensification.

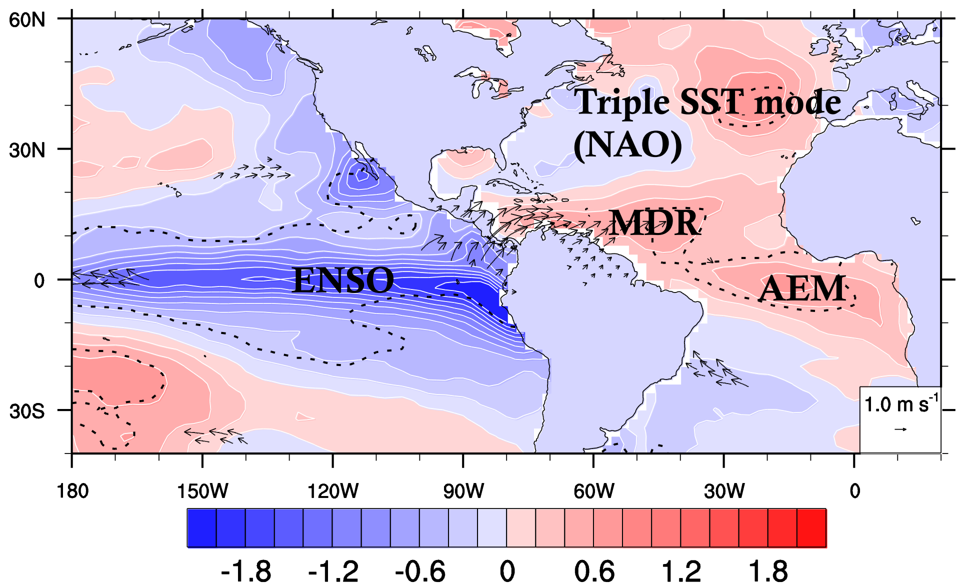

Fig. 8 Composite difference of SST (color) and 10-m wind vector based on M1. Dashed black line indicates the SST signal passes Student-t 95% confidence test. Only 95%-confidence part of wind vectors is plotted.

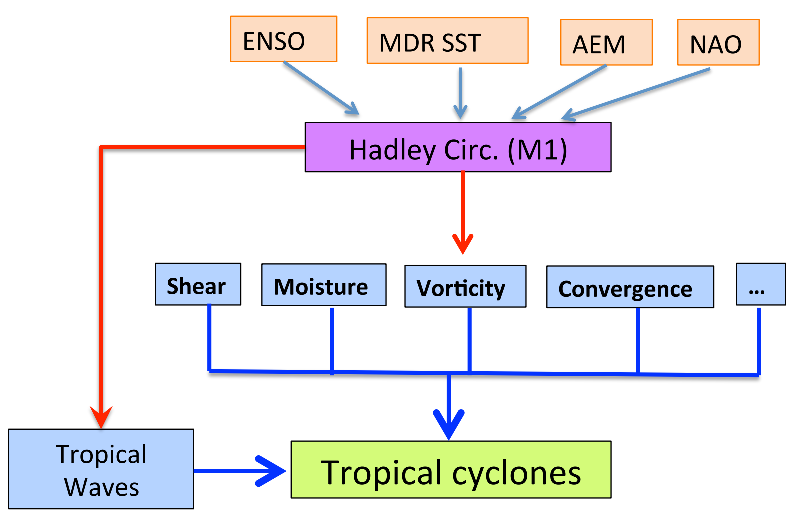

Fig. 9 A Schematic showing how various climate factors may modulate the Atlantic TC activity via the Hadley Circulation.

The variability of the Atlantic HC was examined in the seasonal predictions using the GFDL HiRAM. In the retrospective seasonal predictions, fixed SST fields that include anomalies in early summer were used to drive the HiRAM. The 21-year simulation captures about 80% of the observed variances of the Atlantic TC activity. It is found that the HiRAM simulates reasonably well the dominant mode of the Atlantic HC (M1) (Fig. 10), its linkage with different environmental parameters, and its impacts on TC activity

(Table 1). The predictability of Atlantic TC activity can be explained by the significant correlation between SST in the previous spring and M1 in the hurricane season.

In summary, the Atlantic HC modulates the tropical cyclone activity through both dynamic and thermodynamic controls and provides a unified framework to understand the variability and predictability of Atlantic tropical cyclones.

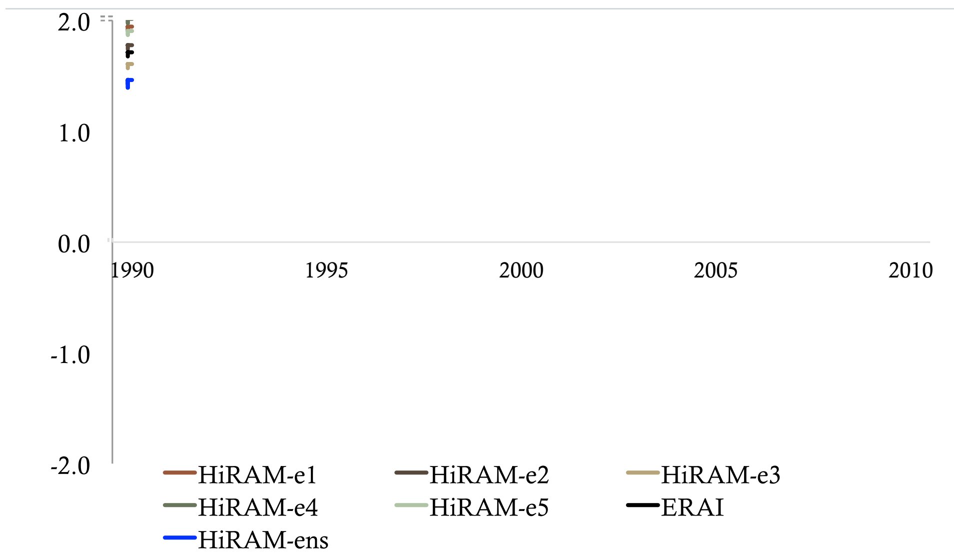

Fig. 10 Time series of the leading EOF mode (M1) of the Hadley Circulation derived from the ERAI, five HiRAM ensembles, and the HiRAM ensemble mean.

Table 1 Correlation between the leading EOF mode and different climate factors, also with the hurricane numbers derived from the ERAI and the HiRAM simulations.

	Shear	RH600	Vort850	SLP	Sahel Precip	Hurr #
ERAI-M1	-0.76	0.47	0.88	-0.84	0.56	0.79
HiRAM-M1	-0.88	0.69	0.70	-0.88	0.40	0.73

IMPACT/APPLICATIONS

Studies in this project contribute to a better understanding of the key physical processes for the MJO simulation/prediction and improved representation of the moist processes in global models, which will lead to better intraseasonal and seasonal prediction of the Navy's global models.

TRANSITIONS

We are working closely with Dr. James A. Ridout and Mr. Tim Whitcomb at the NRL, Monterey. The modifications of the model physics will be vigorously tested and available for transition to the operational model. A package of the diagnostic codes, with a user-friendly interface, will be delivered to the NRL modeling and parameterization team. Some of the diagnostics are expected to be incorporated into the NAVGEM analysis packages by the NRL modeling team.

RELATED PROJECTS

This project is closely related to the other projects under the "Seasonal and Unified Parameterization" and "Seasonal Prediction" DRIs. The model evaluation tools developed can be used by other groups to diagnose the model physical processes and to evaluate the new parameterization schemes.

PUBLICATIONS

Li, Wei-Wei, Zhuo Wang, Melinda S. Peng, and James A. Ridout, 2013: Evaluation of the Navy Operational Global Atmospheric Prediction System (NOGAPS) in Boreal Summer, to be submitted.

Zhang, G., and Zhuo Wang, 2013: Interannual Variability of the Atlantic Hadley Circulation in Boreal Summer and Its Impacts on Tropical Cyclone Activity. J. Climate, in press.